

MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS
WITH IMMERSION PROJECTION LENS

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The invention relates to a microlithographic projection exposure apparatus, comprising an illumination system for generating projection light, a projection lens with which a reticle which can be arranged in an object plane of the projection lens can be imaged on a photosensitive layer which can be arranged in an image plane of the projection lens and is applied to a carrier, and comprising an immersion arrangement for introducing an immersion liquid into an immersion interspace between a last optical element of the projection lens on the image side and the photosensitive layer. The invention further relates to a projection lens of such a microlithographic projection exposure apparatus and to a process for the microlithographic manufacture of microstructured components.

15 A projection exposure apparatus, a projection lens and a process of the above-mentioned type are known from US 4 346 164.

Projection exposure apparatuses, of the kind used for manufacturing large-scale integrated electrical circuits and other microstructured components, project structures contained in a reticle on to a photosensitive layer which may be applied, for example, to a silicon wafer.

One of the fundamental objectives in developing such projection exposure apparatuses is to be able to lithographically define structures of increasingly small dimensions on the photosensitive layer. Small structures
5 give rise to high integration densities, which have a generally favourable effect on the efficiency of the microstructured components produced by means of such apparatuses. The size of the definable structures depends above all on the resolution of the projection lens used.

10 Because the resolution of the projection lens is inversely proportional to the wavelength of the projection light, one approach to increasing resolution is to use projection light with shorter and shorter wavelengths. The shortest wavelengths currently used are in the ultra-
15 violet spectral range and are of 193 nm and 157 nm.

Another approach to increasing resolution is based on the concept of introducing an immersion liquid into the space intervening between the last lens of the projection lens on the image side and the photosensitive layer to be exposed.
20 posed. The immersion liquid preferably has the same refractive index as the photosensitive layer, whereby the numerical aperture is enlarged

The projection exposure apparatus known from the above-mentioned US 4 346 164 has for this purpose an upwardly
25 open container which holds the carrier with the photosensitive layer applied thereto. The container is filled

with an immersion liquid and is so arranged that the last optical element of the projection lens on the image side can be immersed in the liquid.

It has been shown, however, that although resolution can be increased with the aid of the immersion method the contrast of the structures imaged on the photosensitive layer leaves something to be desired.

It is therefore the object of the invention to specify a projection exposure apparatus with which the advantages of the immersion method can be exploited without having to accept significant losses in contrast.

In a projection exposure apparatus of the above-mentioned type this object is achieved in that the projection lens includes a transmission filter which is so designed and arranged in the projection lens that rays which enter the immersion interspace from the last optical element on the image side at an angle of incidence α are attenuated more strongly the smaller the angle of incidence α is.

The invention is based on the discovery that the immersion liquids which come into consideration, e.g. water or certain oils, are not completely transparent to the projection light used but have a significant absorption coefficient differing from zero. This causes a light ray passing through the immersion liquid to be absorbed more

strongly the longer the path travelled by the light ray in the immersion liquid.

Because of the imaging characteristic of the projection lens, rays from different directions strike every image point on the photosensitive layer. Rays which enter the immersion interspace parallel to the optical axis are less strongly attenuated than rays which impinge on the image point concerned at an angle with respect to the optical axis. This is connected to the fact that the photosensitive layer is arranged in the image plane of the projection lens and is therefore flat. Consequently, for a ray which, starting from a point on the image-side face of the last optical element on the image side, passes through the immersion liquid, the path travelled in the immersion liquid is longer the larger the angle of incidence at which the ray enters the immersion interspace with respect to the optical axis. This is also the case, of course, if the point in question is located on a face which is not flat but curved.

If no corrective measures are taken, such an angle-dependent reduction of radiation intensity for rays impinging at an angle on an image point causes the entire imaging process to lose contrast.

With the transmission filter according to the invention, by contrast, rays of projection light which enter the immersion interspace at an angle of incidence α with re-

spect to the optical axis are more strongly attenuated the smaller the angle of incidence α . A lower overall dependence of radiation intensity on ray direction is thereby achieved. With appropriate design of the transmission filter it can even be achieved that the rays of projection light are attenuated in such a way that, for all arising angles of incidence α , the rays have substantially the same radiation intensity on striking the photosensitive layer.

10 The transmission filter may be arranged, for example, at least approximately in a field plane, e.g. in the vicinity of the image plane, of the projection lens and have an angle-dependent transmittance which increases with increasing angles of the rays with respect to the optical
15 axis.

Alternatively, a transmission filter in the form of a normal neutral density filter may be used which is arranged at least approximately in a pupil plane of the projection lens and the transmittance of which increases with increasing distance from an optical axis of the projection lens. This arrangement makes use of the fact that, with a transmission filter arranged in a pupil plane, rays which enter the immersion interspace at a predefined angle of incidence with respect to the optical
20 axis can be attenuated in a specified manner.
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For example, all principal rays, i.e. rays which intersect the optical axis in the pupil plane, exit the projection lens parallel to the optical axis and therefore impinge perpendicularly on the image plane. For this reason the principal rays travel the shortest distance in the immersion liquid and consequently are least attenuated in their radiation intensity by the immersion liquid. To compensate for this, the transmission filter preferably has the lowest transmittance in the region of the optical axis. As a result, the principal rays are most strongly attenuated by the transmission filter and are least attenuated by the immersion liquid. By contrast, rays which pass through regions of the pupil plane further removed from the optical axis impinge on the image plane at larger angles and are therefore subjected to stronger absorption by the immersion liquid. These rays are therefore less attenuated by the transmission filter.

On a transmission filter arranged in a pupil plane, each distance from the optical axis has associated with it a particular angle of incidence at which the rays enter the immersion interspace. To this extent the azimuth angle at which a ray passes through the transmission filter is immaterial. For this reason the transmittance of such a transmission filter can have a rotationally symmetrical progression with respect to the optical axis. In the case of a transmission filter arranged close to the field, the angular dependence of the transmission capability is preferably field-independent.

If the image-side face of the last optical element on the image side is disposed parallel to and at a distance d from the image plane, the dependence of attenuation on the angle of incidence α is preferably given by a transmission function $T(\alpha)$ which depends on the absorption constant k of the immersion liquid and on distance d .

In this case, the particular transmission function $T(\alpha)$ can be given by the equation

$$T(\alpha) = T_0 \cdot \exp(kd/\cos(\alpha)) ,$$

where T_0 is a constant. This constant should preferably be selected such that for those rays of projection light which enter the immersion interspace at the largest possible angle of incidence α_{\max} with respect to the optical axis, the transmission filter has maximum transmittance, preferably approaching 100%. In this case the constant T_0 is given by

$$T_0 = \exp(-kd/\cos(\alpha_{\max})) .$$

Further advantages and features will be apparent from the following description of an embodiment with reference to the drawings, in which:

Fig. 1 shows a meridional section through a projection exposure apparatus according to the invention

in a highly simplified representation which is not to scale;

Fig. 2 shows an enlarged portion of the projection exposure apparatus represented in Fig. 1;

5 Fig. 3 is a plan view of a transmission filter which has transmittance increasing radially towards the outside;

10 Fig. 4 shows a graph in which the attenuation generated by the transmission filter shown in Fig. 3 is plotted in dependence on the angle of incidence with respect to the optical axis with which projection light enters an immersion interspace; and

15 Fig. 5 shows an enlarged portion of a projection exposure apparatus according to a different embodiment in a representation analogous to that in Fig. 2.

20 Fig. 1 shows a meridional section through a microlithographic projection exposure apparatus designated as a whole by 10 in a highly simplified representation. The projection exposure apparatus 10 includes an illumination system 12 for generating projection light 13, which includes a light source 14, an illumination lens system indicated by 16 and a diaphragm 18. In the embodiment il-

lustrated the projection light has a wavelength of 193 nm. The projection exposure apparatus 10 further includes a projection lens 20 containing a multiplicity of lenses, only some of which are indicated by way of example in
5 Fig. 1 for the sake of clarity, and which are denoted by L1 to L5. The projection lens 20 is used to image a reticle arranged in an object plane 22 of the projection lens 20 on a reduced scale on a photosensitive layer 26 which is arranged in an image plane 28 of the projection lens
10 and is applied to a carrier 30.

The carrier 30 is fixed to the bottom of an upwardly open vat-like container 32 which is movable parallel to the image plane 28 by means of a displacement device in a manner not illustrated in detail. The container 32 is
15 filled with an immersion liquid 34 to a level at which the last lens L5 of the projection lens 20 on the image side is immersed in the immersion liquid 34 during operation of the projection exposure apparatus 10. Instead of a lens, the last optical element of the projection lens
20 on the image side may be e.g. a plane-parallel closing plate.

The container 32 is connected via a feed line 36 and a discharge line 38 to a processing unit 40 in which a circulation pump and a filter for cleaning immersion liquid
25 34 are contained. The processing unit 40, the feed line 36, the discharge line 38 and the container 32 together form an immersion arrangement denoted by 42 in which the

immersion liquid 34 circulates while being purified and maintained at a constant temperature. The refractive index of the immersion liquid, which may be e.g. water or an oil, approximately coincides with the refractive index of the photosensitive layer 26. Through the immersion of the lens L5 in the immersion liquid 34 the projection lens can be designed with a larger numerical aperture, so that especially small structures can be defined on the photosensitive layer 26 using the projection exposure apparatus 10.

In the embodiment illustrated, the reticle 24 is a phase mask with which the structures contained therein influence, not the intensity, but the phase of projection light passing through same. Because the reticle 24 acts as a diffraction grating for the projection light 13, different orders of diffraction emanate from each point on the reticle. Moreover, the reticle 24 is so designed that substantially the totality of projection light 13 impinging on one point on the reticle 24 is diffracted into the diffraction orders $m = 0$, $m = +1$ and $m = -1$.

This is illustrated in Fig. 1 for a point OP which is located on the optical axis 44 of the projection lens 20. The diffractive order $m = 0$ corresponds to undiffracted projection light and is represented as the ray S_0 , while the diffraction orders $m = +1$ and $m = -1$ are represented by diffracted rays S_{+1} and S_{-1} . The further ray path of

the rays S_0 , S_{+1} and S_{-1} is indicated only schematically in the projection lens 20.

In Fig. 2 an enlarged portion of the end of the projection lens 20 on the image side is illustrated. It can be
5 seen that the image-side plane face 46 of the last lens L5 of the projection lens 20 on the image side is immersed in the immersion liquid 34 which fills an immersion interspace 35 between the last lens L5 on the image side and the photosensitive layer 26. The ray S_0 which is
10 disposed along the optical axis 44 travels the shortest possible distance d_0 in the immersion liquid 34, i.e. the distance between the photosensitive layer 26 and the plane face 46 of the lens L5 parallel thereto.

The two rays S_{+1} and S_{-1} , by contrast, enter the immersion
15 interspace 35 at an angle of incidence α with respect to the optical axis 44. Because of this oblique entry into the immersion interspace 35 the distance travelled therein is d_α , where

$$d_\alpha = d_0 / \cos(\alpha) \quad . \quad (1)$$

Because the absorption coefficient k of the immersion
20 liquid 34 is homogeneous and isotropic, the rays S_{+1} and S_{-1} are more strongly attenuated by the immersion liquid 34 because of the longer distance d_α , than the central ray S_0 .

If the radiation intensity of the rays S_0 , S_{+1} and S_{-1} on entering the immersion interspace 35 is I_0 in each case, their radiation intensity $I(\alpha)$ after passing through the immersion liquid 34 is yielded by

$$I(\alpha) = I_0 \cdot \exp(-kd_0/\cos(\alpha)) \quad (2)$$

5 Through the greater attenuation of the rays S_{+1} and S_{-1} inclined at an angle of incidence α with respect to the optical axis 44, therefore, less light from the orders of diffraction $m = +1$ and $m = -1$ reaches an image point IP on the photosensitive layer 26 than light from the dif-
10 fractive order $m = 0$. As a result the image produced on the photosensitive layer 26 has lower contrast than if the intensities of radiation were distributed uniformly over the orders of diffraction.

To ameliorate this situation and to achieve such uniform-
15 ity a transmission filter 50 mounted in a filter holder 52 is arranged in a pupil plane 48 of the projection lens 20. The transmission filter 50, which is shown in a plan view in Fig. 3, has a transmittance which increases with increasing distance from the optical axis 44. In the plan
20 view in Fig. 3 this is indicated by a plurality of concentric circles the spacing of which increases towards the outside

In the transmission filter 50 shown as an example in Fig. 3 the transmittance T is rotationally symmetrical and is

therefore a function only of the radial distance r from the optical axis 44:

$$T = T(R) . \quad (3)$$

Because of the arrangement of the transmission filter 50 in the pupil plane 48, rays which pass through the transmission filter 50 at a relatively large distance from the optical axis 44 enter the immersion interspace 35 at a larger angle of incidence α than rays which pass through the transmission filter 50 close to the optical axis 44. Because the transmittance of the transmission filter 50 is lower in that region, the last-mentioned rays are attenuated more strongly than rays which enter the immersion interspace 35 at a larger angle of incidence α with respect to the optical axis. In this way it is achieved that the attenuation according to equation (2), which increases with increasing angle of incidence α , is overlaid by an attenuation generated by the transmission filter 50, which decreases with increasing angle of incidence α . As a result, more uniform overall radiation intensity for the rays of the different diffractive orders is produced.

The intensity of radiation becomes especially uniform if the product of the attenuation resulting from absorption in the immersion liquid 34 according to equation (2) and the attenuation resulting from absorption in the transmission filter 50 is a constant:

$$T(\alpha) \cdot I(\alpha) = \text{const} . \quad (4)$$

In this equation $T(\alpha)$ designates the transmittance of the transmission filter 50 as a function of the angle of incidence α at which the rays enter the immersion interspace 35.

- 5 From equations (3) and (4) the transmittance $T(\alpha)$ is then yielded as

$$T(\alpha) = T_0 \cdot \exp(-kd_0/\cos(\alpha)) . \quad (5)$$

So that as little projection light 13 as possible is absorbed overall by the transmission filter 50 the constant T_0 is preferably so defined that, at least for the rays
 10 which enter the immersion interspace 35 at the largest possible angle of incidence α_{\max} , the transmission filter has a highest possible transmittance, preferably $T(\alpha_{\max}) \approx 1$. Insertion into the equation (5) then yields for the constant T_0 the relation

$$T_0 = \exp(-kd_0/\cos(\alpha_{\max})) . \quad (6)$$

- 15 In Fig. 4 the progression of transmittance $T(\alpha)$ is plotted as a function of the angle of incidence α at which the rays enter the immersion interspace 35 with respect to the optical axis. It has been assumed that the distance from the surface 46 of the lens L5 to the photosensitive layer 26 $d_0 = 4$ mm. The calculation is based fur-
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ther on the assumption that water is used as the immersion liquid 34 and is exposed to projection light having a wavelength of 193 nm. The absorption coefficient k is then $k = 0.0321$ 1/cm. A value of 65° was used for the maximum arising angle of incidence α_{\max} .

It can be seen from the graph in Fig. 4 that transmittance $T(\alpha)$ has the exponential progression yielded by equation (5). In terms of absolute values, however, the increase is relatively small, since even for an angle of incidence $\alpha = 0^\circ$ the transmittance is still greater than 0.982.

It should be noted in this connection that the transmittance progression $T(\alpha)$ represented in Fig. 4 is not identical to the radial transmittance progression $T(r)$, as indicated schematically in Fig. 3. The relation between radial distances r and angles of incidence α is predefined by the concrete design of the projection lens 20 and cannot be generalised without further specification. Qualitatively, however, the radial transmittance $T(r)$ has a similar progression to the transmittance $T(\alpha)$ represented in Fig. 4.

Fig. 5 shows in an enlarged section, in a representation analogous to Fig. 2, the image-side end of a projection lens according to a different embodiment of the invention. Parts identical to those in the above-described

projection lens are denoted by the same reference characters.

A transmission filter 50' having angle-dependent transmission capability is fixed (in a manner not represented
5 in detail) to the plane face 46 of the last optical element L5 on the image side. The transmission filter 50' is therefore arranged close to the field, i.e. in the vicinity of the image plane 28. Angle-dependent transmission filters which are arranged in a field plane and which
10 cause angle-dependent attenuation are described in WO 03/02256 of the applicant, the disclosure content of which is included in its full extent in this application.

The angular dependence of the transmission capability is so designed in the case of transmission filter 50' that
15 rays which enter the immersion interspace 35 at a larger angle of incidence α are attenuated less strongly than rays which enter the immersion interspace 35 at a smaller angle of incidence α . With appropriate design of the angular dependence it can be achieved in this case, too,
20 that all rays impinge on the photosensitive layer 26 with approximately the same intensity.

Alternatively the transmission filter 50' may be arranged in a field plane conjugate to the image plane 28, e.g. in the vicinity of the object plane 22 or in an intermediate
25 image plane - if present - of the projection lens 20.

CLAIMS

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1. Microlithographic projection exposure apparatus,
comprising an illumination system (12) for generat-
ing projection light (13), a projection lens (20) with
which a reticle (24) which can be arranged in an object
5 plane (22) of the projection lens (20) can be imaged on a
photosensitive layer (26) which can be arranged in an im-
age plane (28) of the projection lens (20) and is applied
to a carrier (30), and comprising an immersion arrange-
ment (42) for introducing an immersion liquid (34) into
10 an immersion interspace (35) between a last optical ele-
ment (L5) of the projection lens (20) on the image side
and the photosensitive layer (26),

characterized in that

the projection lens (20) includes a transmission filter
15 (50) which is designed and arranged in the projection
lens (20) in such a way that rays (S_0 , S_{+1} , S_{-1}) which en-
ter the immersion interspace (35) from the last optical
element (L5) on the image side at an angle of incidence α
are attenuated more strongly the smaller the angle of in-
20 cidence α is.

2. Projection exposure apparatus according to claim 1,
characterized in that the transmission filter (50)
is arranged at least approximately in a field plane of

the projection lens (20) and has angle-dependent transmittance which increases with increasing ray angles with respect to the optical axis (44) of the projection lens (20).

5 3. Projection exposure apparatus according to claim 1, characterized in that the filter is a transmission filter (50) which is arranged at least approximately in a pupil plane (48) of the projection lens (20) and the transmittance of which increases with increasing distance
10 from an optical axis (44) of the projection lens (20).

4. Projection exposure apparatus according to claim 3, characterized in that the transmittance of the transmission filter (50) has a rotationally symmetrical progression with respect to the optical axis (44).

15 5. Projection exposure apparatus according to any one of the preceding claims, characterized in that the transmission filter (50) attenuates the rays (S_{+1} , S_0 , S_{-1}) of the projection light (13) in such a way that for all occurring angles of incidence α the rays (S_{+1} , S_0 ,
20 S_{-1}) have substantially the same radiation intensity when impinging on the photosensitive layer (26).

6. Projection exposure apparatus according to any one of the preceding claims, characterized in that the dependence of attenuation on the angle of incidence α is
25 yielded by a transmission function $T(\alpha)$ which depends on

the absorption constant k of the immersion liquid (34) and on the distance d between the last optical element (L5) of the projection lens (20) on the image side and the photosensitive layer (26).

- 5 7. Projection exposure apparatus according to claim 6, characterized in that the transmission function $T(\alpha)$ is at least approximately yielded by

$$T(\alpha) = T_0 \exp(-kd/\cos(\alpha)) ,$$

where T_0 is a constant.

- 10 8. Projection exposure apparatus according to claim 7, characterized in that the constant T_0 is at least approximately yielded by

$$T_0 = \exp(-kd/\cos(\alpha_{\max})) ,$$

- 15 where α_{\max} is the maximum angle of incidence at which rays (S_{+1} , S_0 , S_{-1}) enter the immersion interspace (35).

9. Projection lens of a microlithographic projection exposure apparatus with which a reticle (24) which can be arranged in an object plane (22) of the projection lens (20) can be imaged on a photosensitive layer (26)
20 which can be arranged in an image plane (28) of the projection lens (20) and is applied to a carrier (30),

characterized in that

the projection lens (20) has a transmission filter (50) which is designed and arranged in the projection lens in such a way that rays (S_0 , S_{+1} , S_{-1}) which enter the immersion interspace (35) from the last optical element (L5) on the image side at an angle of incidence α are attenuated more strongly the smaller the angle of incidence α is.

10. Process for the microlithographic manufacture of microstructured components comprising the following steps:

- a) providing a carrier (30) on which a layer (26) of a photosensitive material is applied at least partially;
- 15 b) providing a reticle (24) containing structures to be imaged;
- c) projection of at least a part of the reticle (24) onto an area of the layer (26) using a projection exposure apparatus (10) according to any one of
20 claims 1 to 8.

11. Microstructured component which is manufactured using the process according to claim 10.

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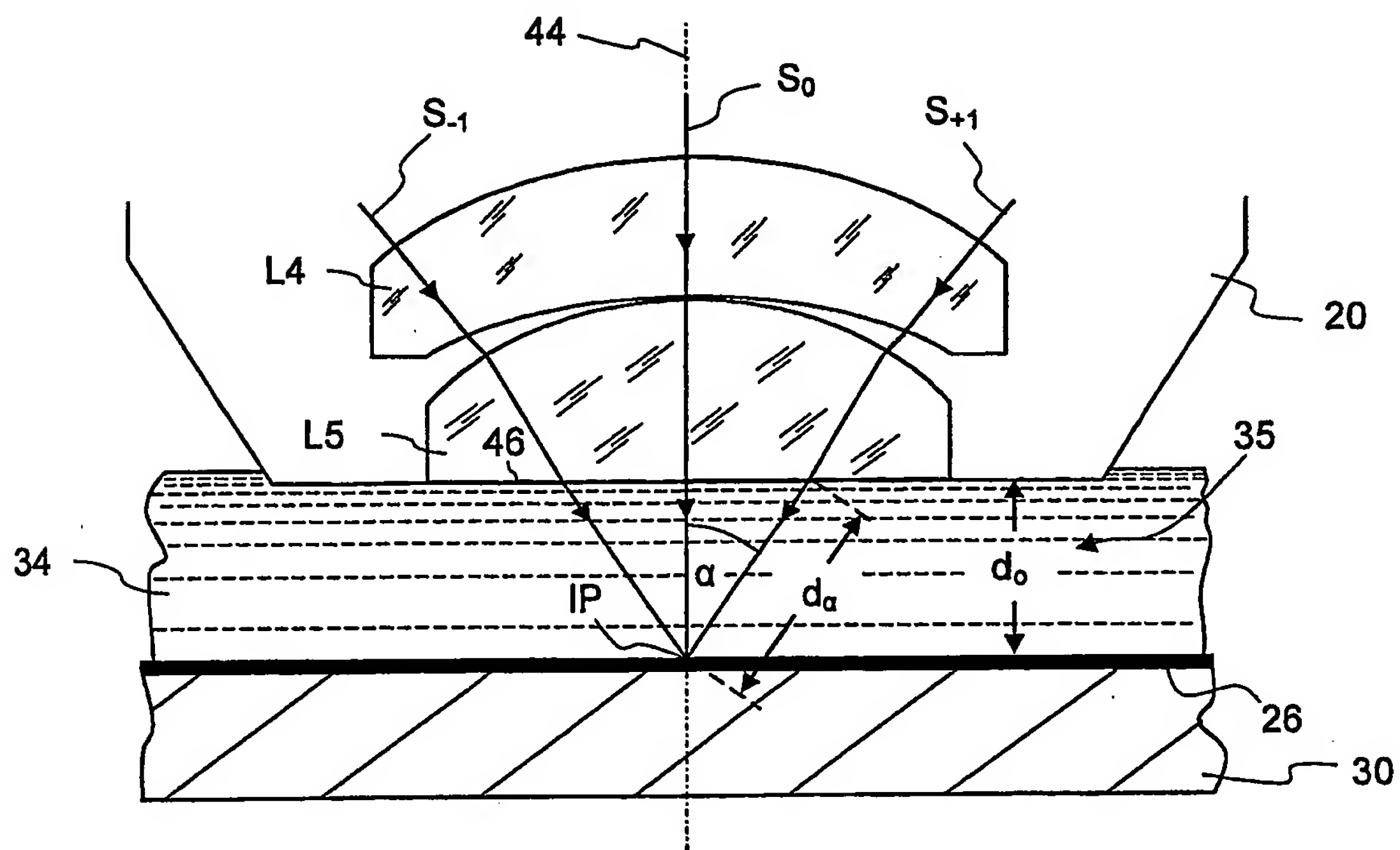


Fig. 2

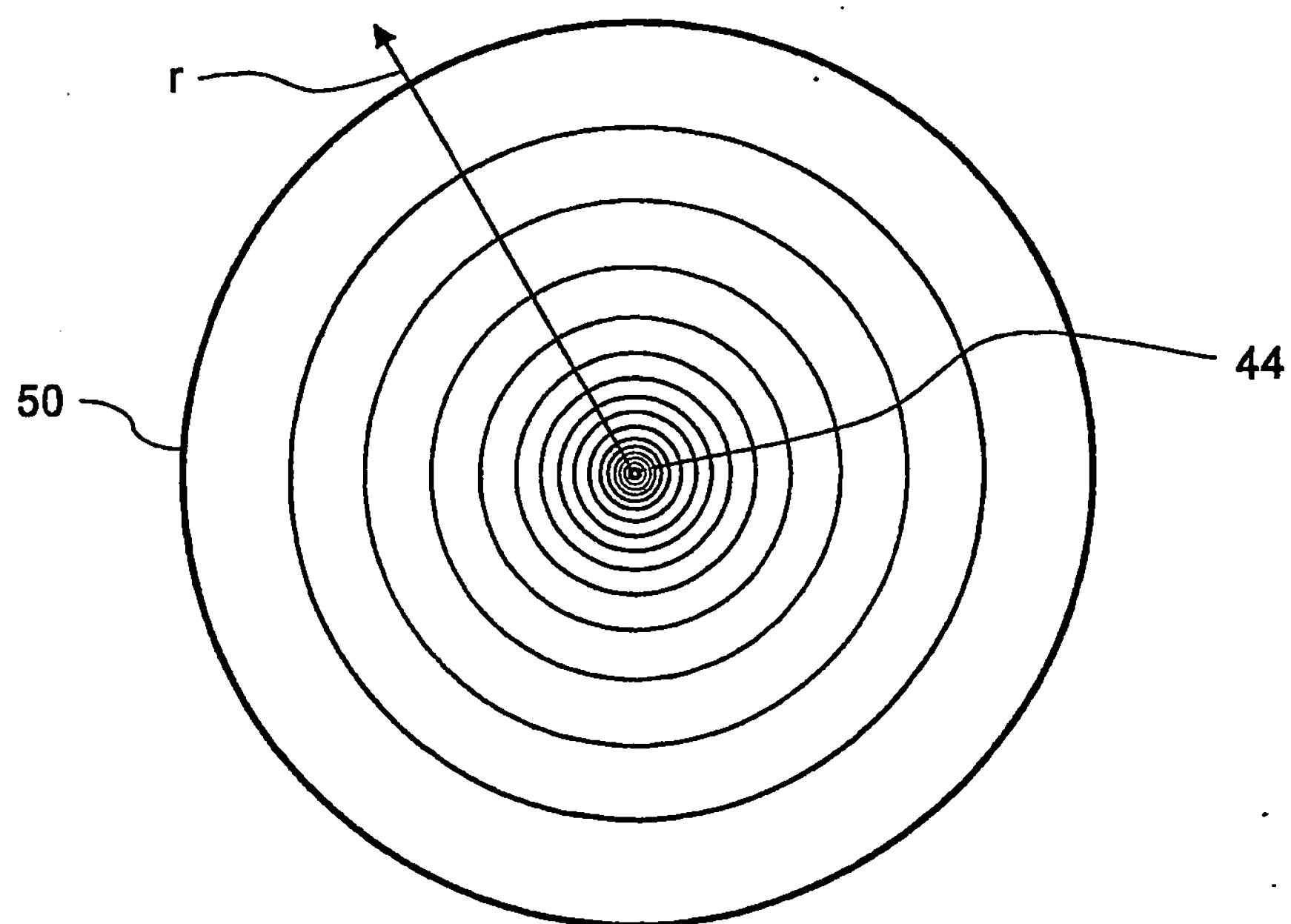


Fig. 3

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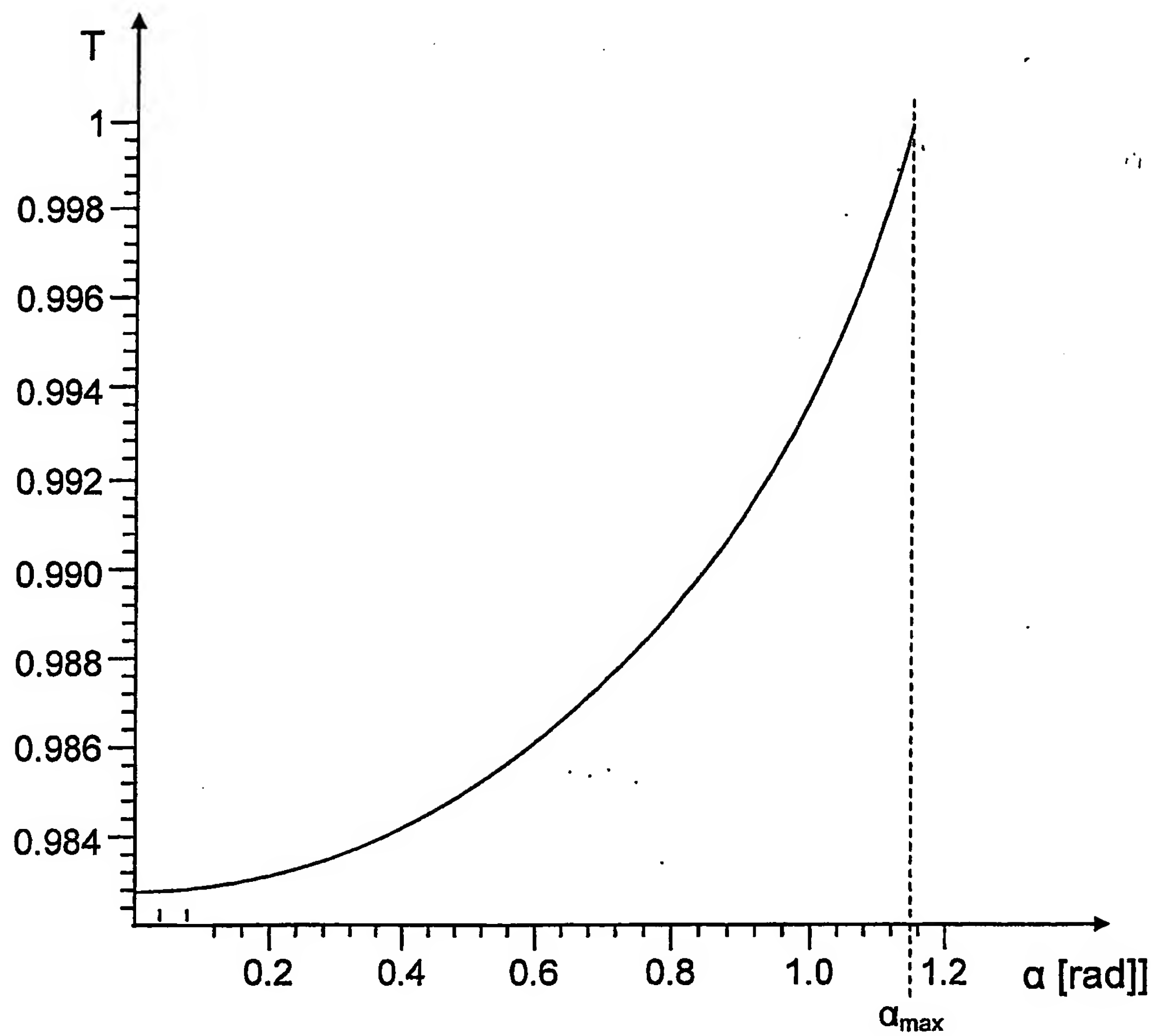


Fig. 4

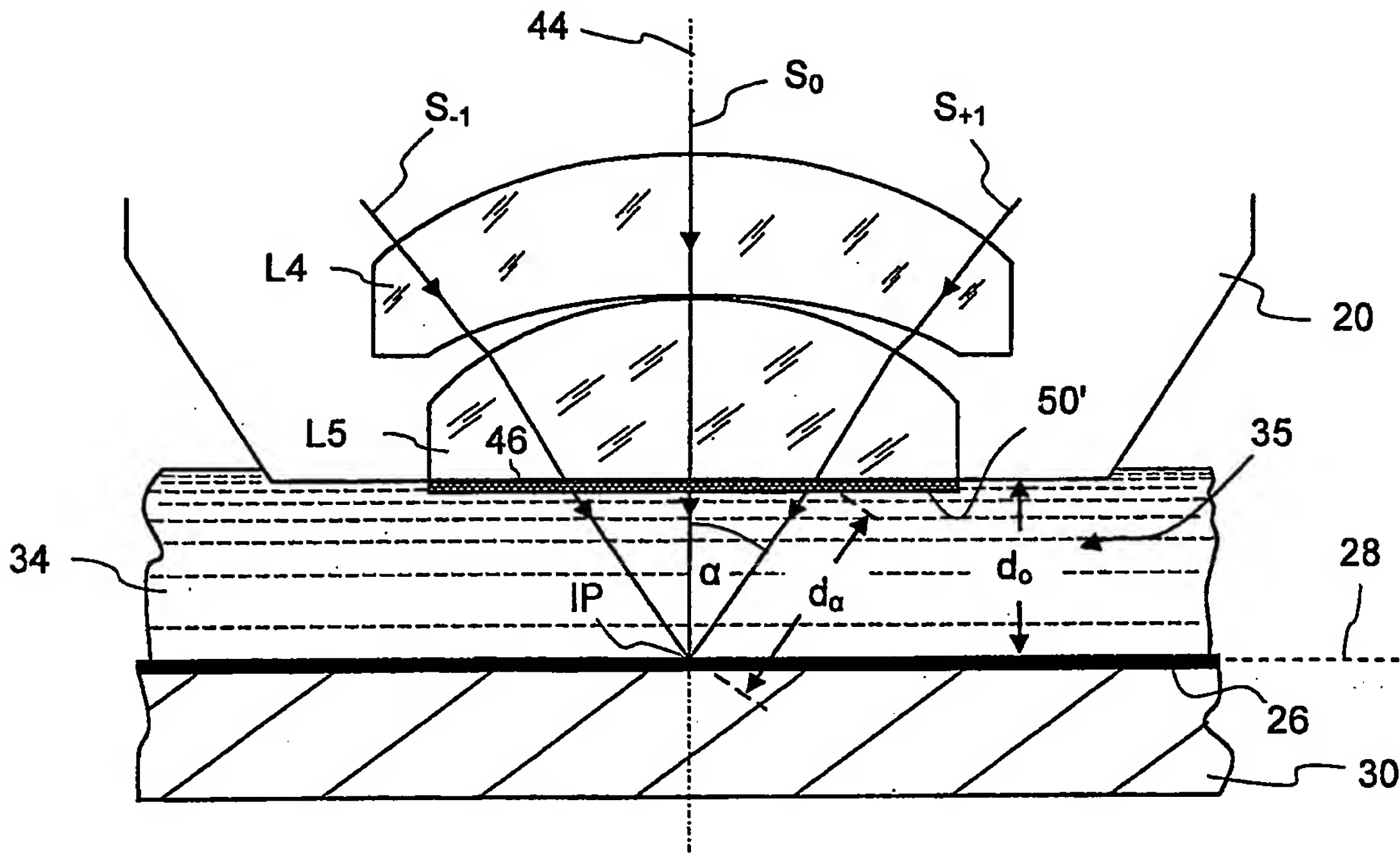


Fig. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP2004/001779

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G03F7/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 715 039 A (FUKUDA HIROSHI ET AL) 3 February 1998 (1998-02-03) column 2, line 43 - line 49	11
A	column 8, line 60 - line 67 column 14, lines 39-45; figure 13	1
A	WO 01/02907 A (SMITH BRUCE W) 11 January 2001 (2001-01-11) page 7, line 5 - line 9; figure 9	
A	WO 03/092256 A (CARL ZEISS SMT AG ; BRUNOTTE MARTIN (DE); GRAEUPNER PAUL (DE); GRAESCH) 6 November 2003 (2003-11-06) cited in the application figures 2,2a	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
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- *O* document referring to an oral disclosure, use, exhibition or other means
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- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *&* document member of the same patent family

Date of the actual completion of the international search

20 January 2005

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/EP2004/001779

Patent document cited in search report		Publication date		Patent family member(s)		Publication date
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			EP	1203264 A1		08-05-2002
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			WO	0102907 A1		11-01-2001
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			WO	03092256 A2		06-11-2003